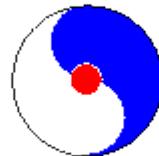


HET Lattice Activities

Taku Izubuchi



RIKEN BNL Research Center

Lattice Gauge theories

- True **first-principles** non-perturbative computations
- **Indispensable bridge** between **experiment and theory**, allowing new physics to be discovered. A part of **precision frontier**.
QCDSP ~1Tflops
- Also explores theories other than QCD.
- **Symmetries** are key ingredients
(gauge symmetry, chiral symmetry of quarks)

LGT @ BNL

'79 Lattice Gauge simulation (M. Creutz)

'97~ Domain-Wall Fermions (DWF) Nf=0 quenched
Blum & Soni

'99~ Riken-BNL-Columbia (RBC)

'02~ DWF **Nf=2** up, down quarks RBC

'05~ DWF **Nf=2+1** up, down, strange quarks (all light quarks) RBC/UKQCD



QCDOC ~10Tflop BlueGene/L,P ~ 10-100 Tflops

RBC/UKQCD collaboration

BNL

C. Jung, T. Izubuchi, (T. Misumi),
A. Soni, R. Van de Water, O. Witzel

RIKEN-BNL Research Center (RBRC)

Y. Aoki, T.I, C. Lehner, S. Ohta,
E. Shintani

Columbia Univ.

N. Christ, X-Y. Jin, C.Kim, M. Li,
M. Lightman, Q. Liu,
R. Mawhinney, H. Peng,

Univ. Connecticut

T.Blum, T. Ishikawa, R. Zhou

Univ. Virginia C. Dawson

Harvard Univ. M. Clark

Yale Univ. M. Lin

Univ. Edinburgh

D. Antonio, P. Boyle, Paul Cooney,
A. Hart, A. Kennedy, R. Kenway,
C. Kelly, C. Maynard, B. Pendleton,
J. Wennekers, J. Zanotti

Univ. Southampton

D. Brommel, M. Donnellan, P. Fritzsch,
J. Flynn, E. Goode, C. Sachrajda

Univ. Swansea C. Allton

Univ. Regensburg E. Scholz

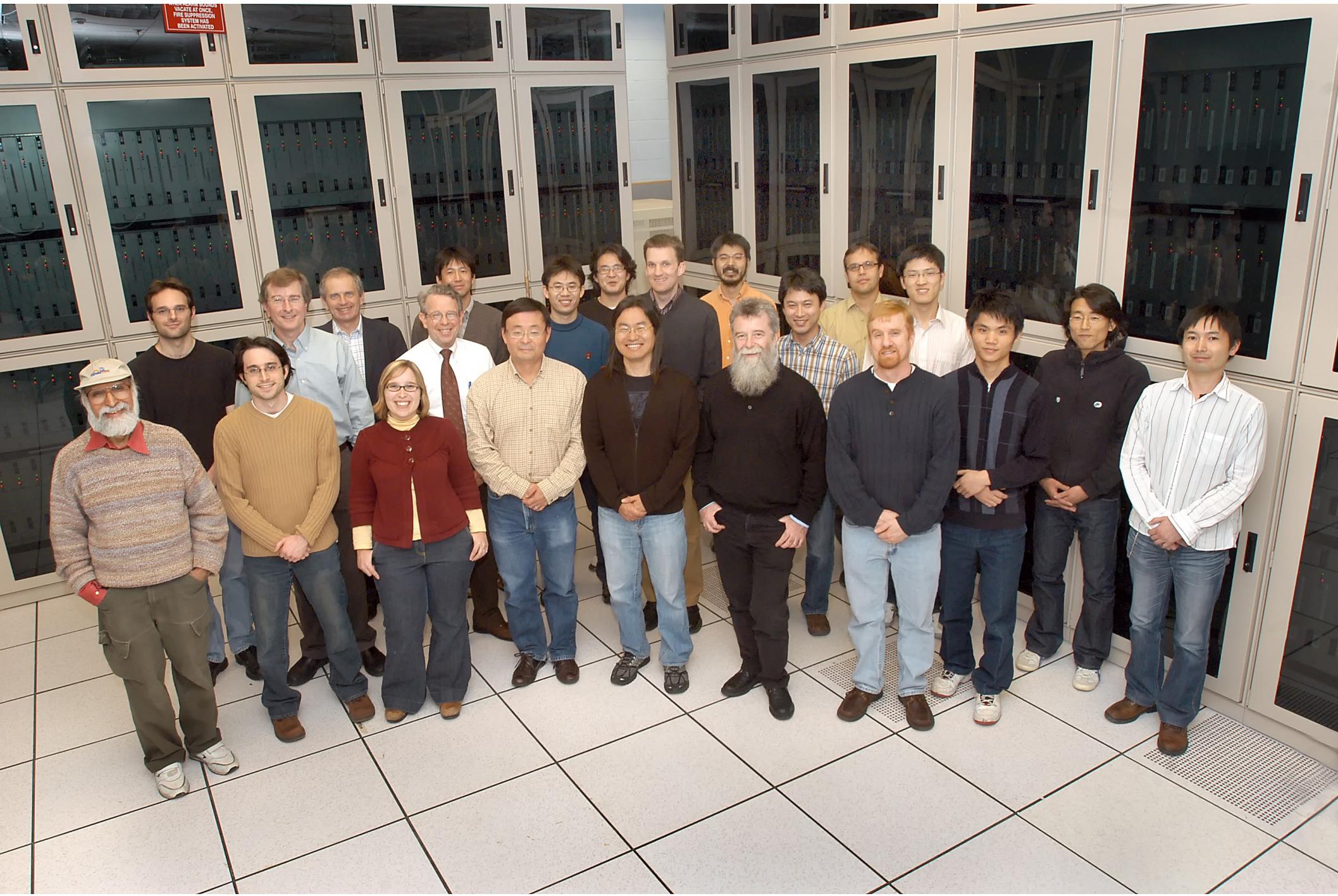
CERN A. Juttner

13 students, 16 PhD theses

RIKEN(Japan) now has a program to support
for PhD students via TI. The use of this new
avenue is being explored with CU & U Conn.

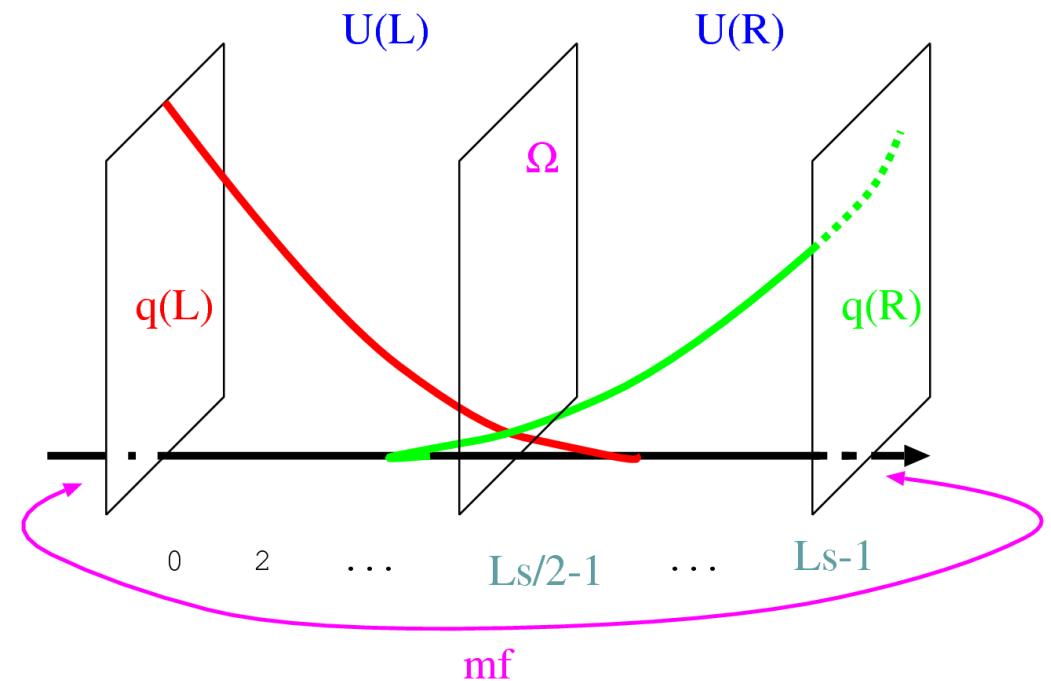
3 plenary talks @ KAON09

5 plenary talks @ LATTICE09



Domain Wall Fermions

- 4D lattice quark utilizing an **extra dimension**
- Almost perfect **chiral symmetry**
 - **Small unphysical mixing** for the **Weak Matrix Elements**
 - Error from discretization is small $O(a^2) \sim$ a few %
 - **Chiral extrapolation** is simpler
- Vacuum polarization effects from up, down, and strange ($N_f=2+1$) quarks are fully incorporated.
- **Unitary** theory at long distance



Computational resources

- QCDOC (DOE + RBRC) 2005-present 10 + 10 TFLOPS peak
- 2005-2007: 13 TFLOPS (peak) year 1 or 2 proposals to USQCD
Nf=2, 2+1 QCD vacuum, WME, B_K, EM,
- 2008: 80 TFLOPS (peak) year 2 proposals
QCD vacuum + pi,K INCITE ALCF 180 M BG/P core hours (70 TFLOPS year)
- 2009: 50 TFLOPS (peak) year 4 proposals
QCD vacuum + pi, K INCITE ALCF 78 M BG/P core hours (30+3 TFLOPS year)
Static-B, CPV 10 M QCD node hours (0.93 TFLOPS year)
Relativistic-B 2.6 M 6n-node hours (5.9 TFLOPS year)
- 2010: 97 TFLOPS (peak) year 7 proposals
QCD vacuum + pi, K INCITE ALCF 75 M BG/P core hour (30+2 TFLOPS year)
EM, Nucleon, Static-B **RICC(RIKEN/Japan)** 9.15 M RICC core hours
(12 TFLOPS year)
EM, Nucleon RICC 17.4 M RICC core hours (under review) (42 TFLOPS year)

Relativistic-B 4 M Jpsi core hours (4 TFLOPS year)

EM 7 M Jpsi core hours (7 TFLOPS year)
- About a factor of 8 larger computational resources
2007 → 2010

QCDCQ (QCD with Chiral Quarks) status

- Prototype of IBM BlueGene/Q
- Designed and developed by **Columbia Univ, Edinburgh, IBM Watson, RIKEN-BNL**
(synergy b/w **national lab, universities and industry**)
- **200 TFLOPS peak / rack**
(QCDOC **0.8 TFLOPS / rack**, 10 TFLOPS total)
- 75 K Watts / rack
- Dirac operator efficiency on simulator ~ 60 % peak
- **First 512 node (100 TFLOPS peak) operational in 2010 fall**
- Full machine will be available in June 2011
- 4 rack UK machine (800 TFLOPS peak) now funded



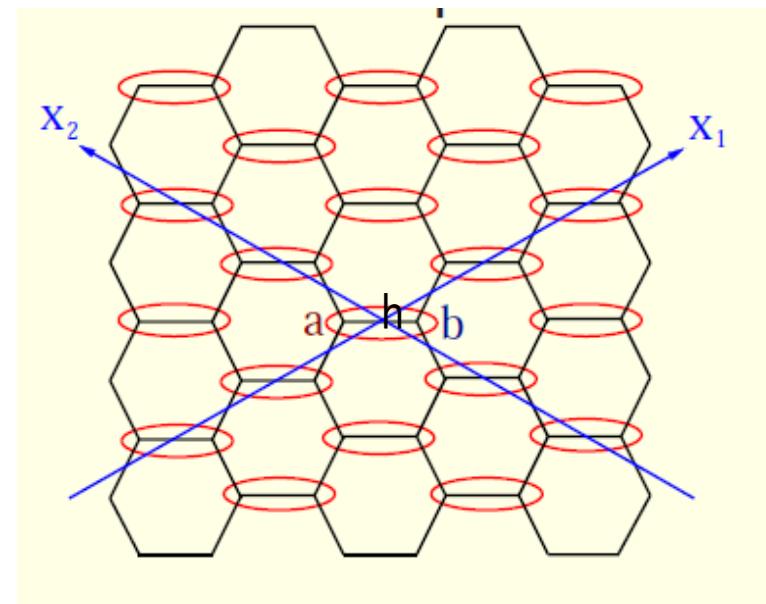
Menu of lattice QCD

- A new lattice Quark [Creutz, Misumi]
- Hadron spectrum
- Chiral Perturbation Theory
SU(3), SU(2)
- Quark masses
- Renormalization/
Scheme matching
- Meson decay constants
- Electro-Magnetic(QED) Effects
- $g(\mu)-2$
- Proton decay
- Proton/Neutron Electric Dipole
moment
- Strange quark contents in
Nucleon (Dark matter detection)
- Flavor Physics, CKM, Electro
Weak Matrix Elements
 - f_K / f_π
 - $K \rightarrow \pi l \nu$ (Kl3)
 - K0-K0 mixing (B_K)
 - $K \rightarrow \pi \pi, \Delta I = 3/2, 1/2 \quad \varepsilon' / \varepsilon$
 - B, D physics
- Strong dynamics
(Technicolor), SUSY

Minimally Doubled Chiral Fermion

[M.Creutz, T. Misumi]

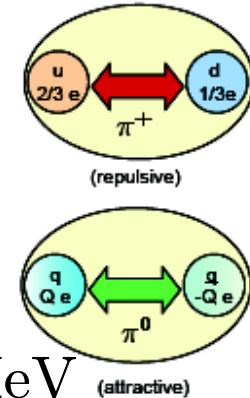
- A two-flavor lattice quarks in 4 dim.
- One exact chiral symmetry
- Protects from additive mass renormalization (robust massless structure), needs to tune one dim-3 operator
- Currently exploring interpolations between variant forms
- Point splitting required for physical meson operators
- Ultra local, expected to allow fast to simulations
- Strong CP and U(1) anomaly [M. Creutz]
- Degenerate light quarks: $Z(N_f)$ singlet discrete chiral symmetry
- $N_f \geq 2$: first order transition required at $\theta = \pi$
- $N_f = 1$: transition absent for $m_q < O(\Lambda_{\text{QCD}})$
- probes reality of the strong CP problem



QCD+QED simulation

[R. Zhou, S. Uno, T. Blum, T. Doi, M. Hayakawa, Tl, N. Yamada,]

- Up down quark has different **electric charge** and **masses**
→ Breaking of **isospin symmetry**



- Isospin breaking effects are accurately measured experimentally

$$\Delta m_\pi = m_{\pi^\pm} - m_{\pi^0} = 4.5936(5)\text{MeV}, \quad m_N - m_P = 1.2933317(5)\text{MeV}$$

- Quark masses. (Strong CP problem)
- Compute Pion/Kaon using Nf=2+1 DWF QCD + QED

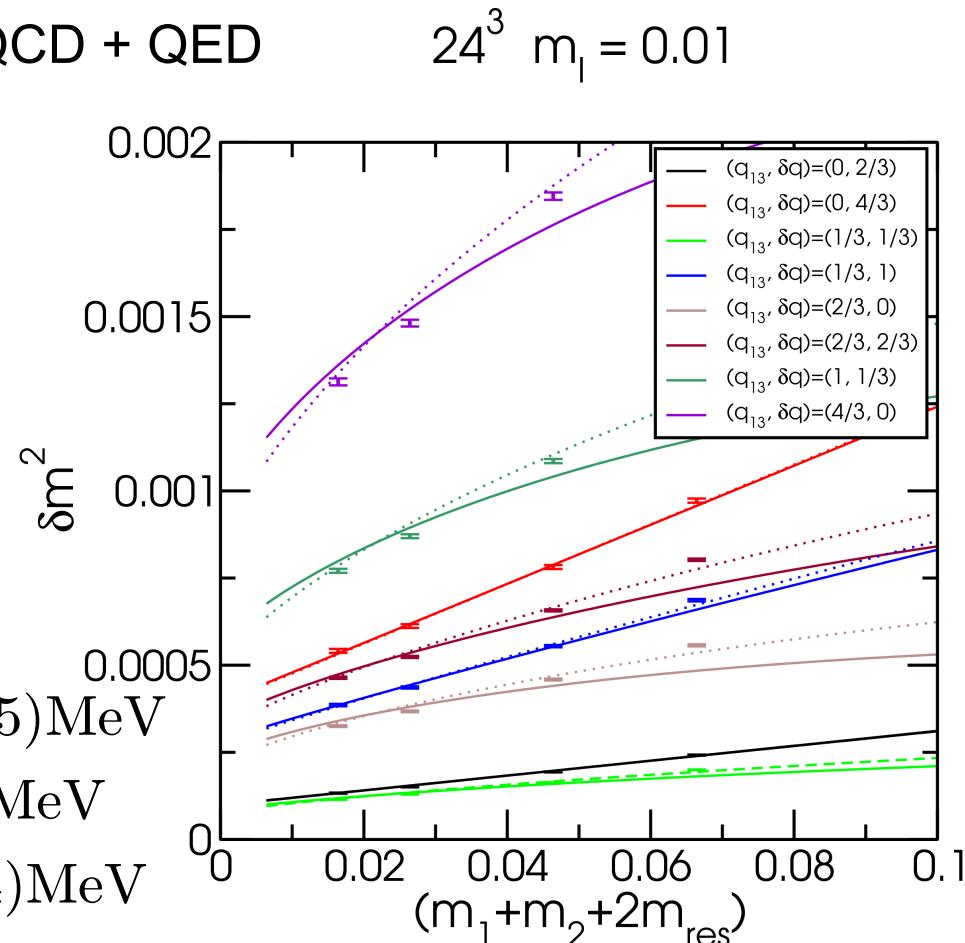
Requiring $m_q < 40$ MeV (70MeV), 48 (120)
partially quenched data points for PS meson survive

- Fit to chiral perturbation theory with EM
(SU(3)+EM and SU(2)+Kaon+EM) to extract quark masses.
- Chiral symmetry is essential to define quark massless points.
- Input:

$$M_{\text{PS}}(m_u, 2/3, m_d, -1/3) = 139.57018(35)\text{MeV}$$

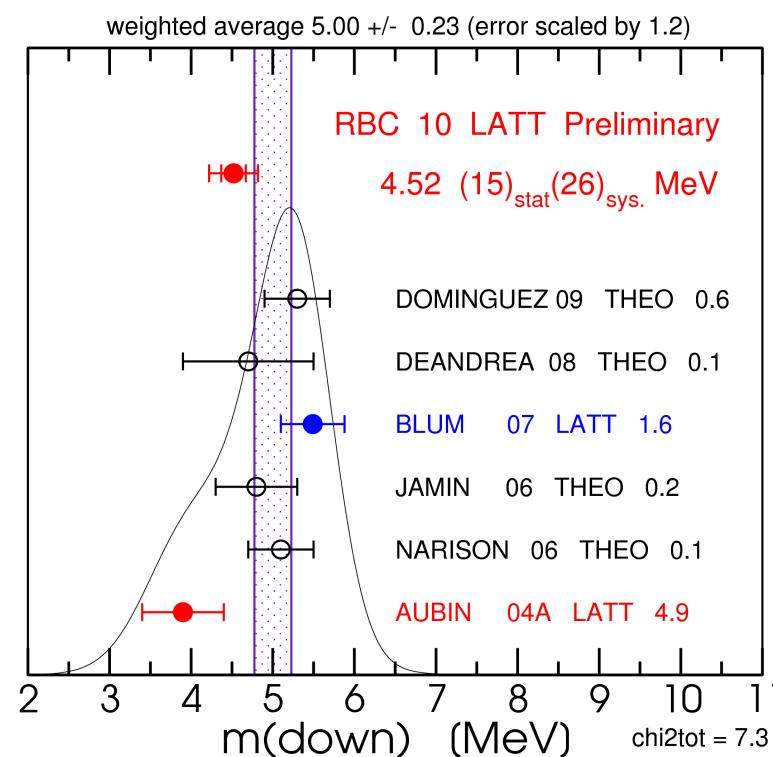
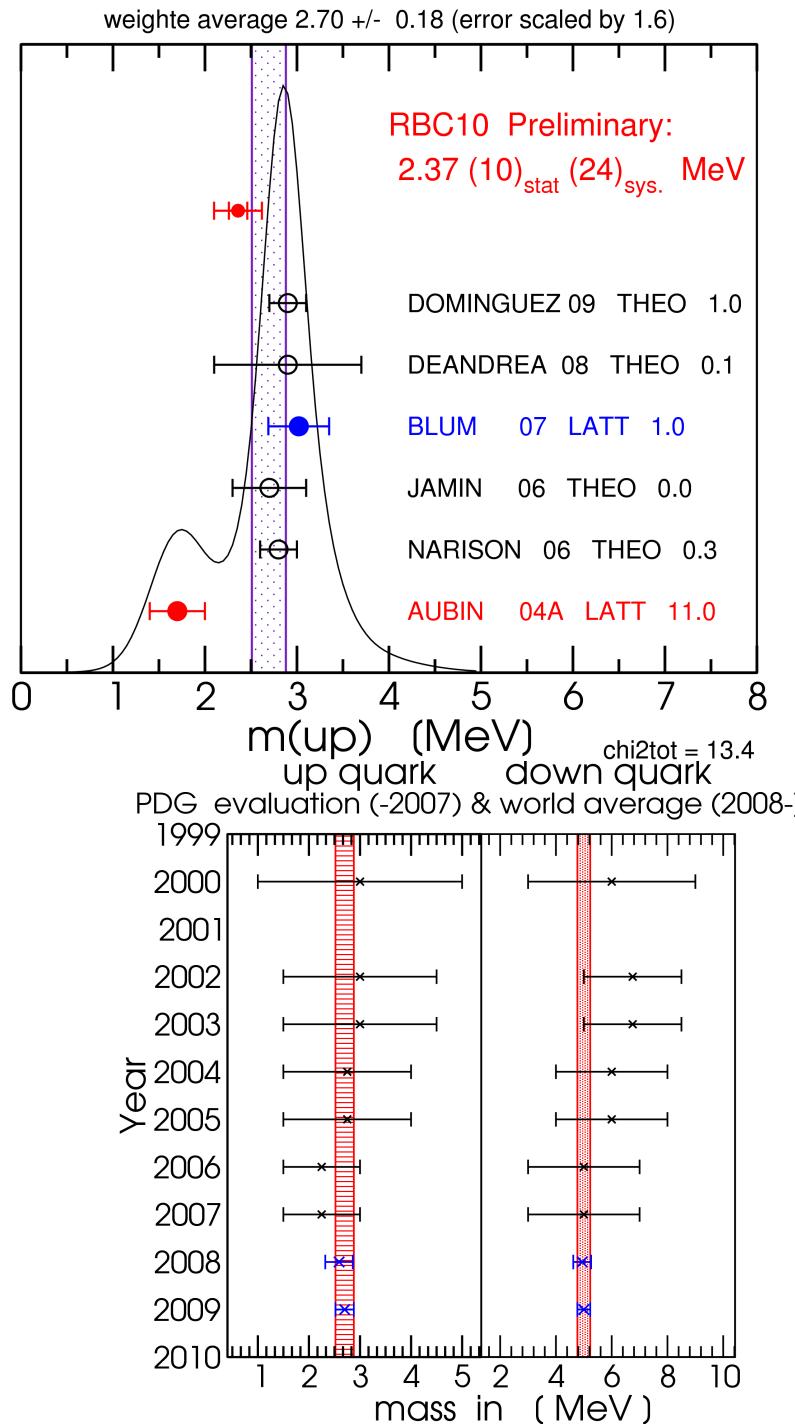
$$M_{\text{PS}}(m_u, 2/3, m_s, -1/3) = 493.673(14)\text{MeV}$$

$$M_{\text{PS}}(m_d, -1/3, m_s, -1/3) = 493.673(14)\text{MeV}$$



Preliminary Quark mass results from lattice QED+QCD

PDGLive 2010 May



- Kaon mass splitting

- Experimentally

$$M_{K^\pm} - M_{K^0} = -3.937(29) \text{ MeV}$$



Theoretical origins

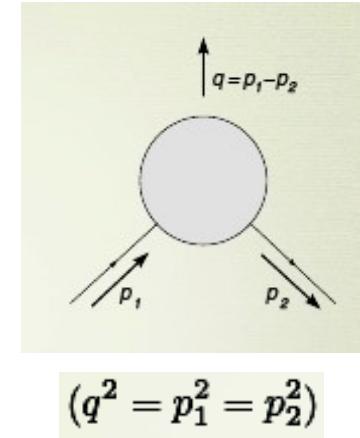
$$\Delta M(m_{\text{up}} - m_{\text{down}}) = -5.7(1) \text{ MeV}$$

$$\Delta M(q_{\text{up}} - q_{\text{down}}) = 1.8(1) \text{ MeV}$$

New Renormalization Schemes

[09 C. Sturm, Y. Aoki, N. Christ, TI, C. Sachrajda, A. Soni]
[10 L. Almeida, C. Sturm]

- Match the normalization of operator on lattice and in continuum theory (MS) via RI/SMOM schemes
calculate the 3 pt amplitudes for a momentum configuration (SMOM) on lattice non-perturbatively, and in continuum theories.

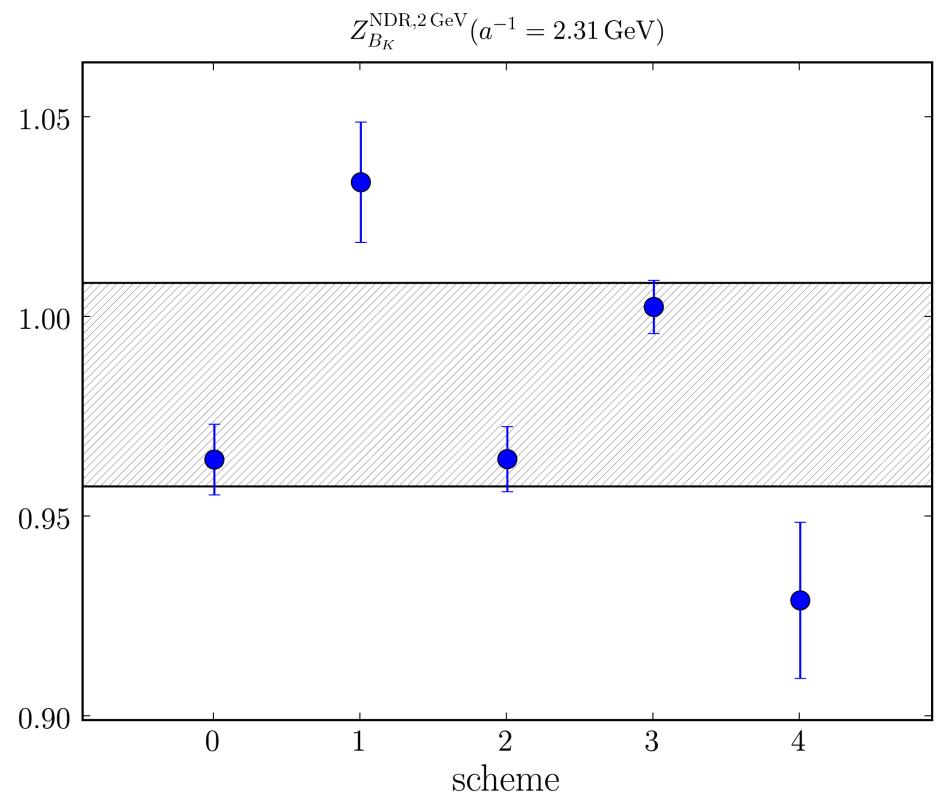
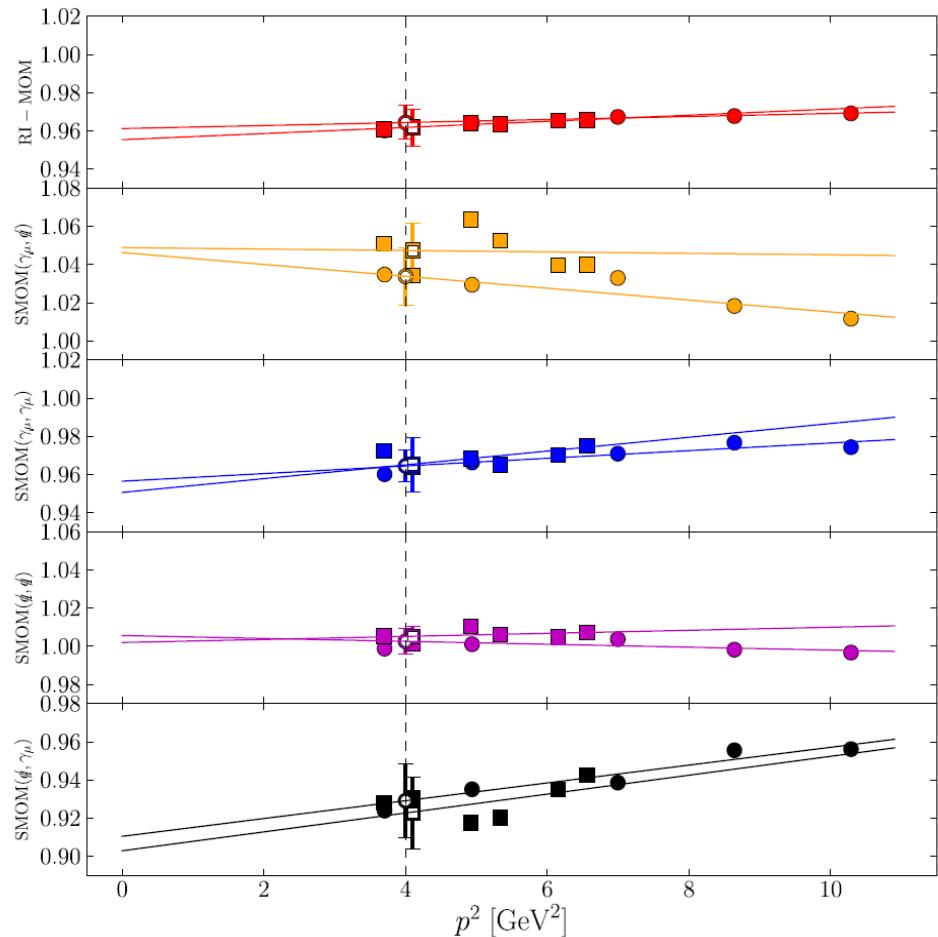


- We find symmetric momentum (SMOM) configuration is useful to reduce one of the dominant systematic errors due to IR effects.
- Quark mass renormalization error

$\sim 10\% \text{ (MOM)} \rightarrow \sim 5\% \text{ (SMOM)} \rightarrow \sim 2\% \text{ (SMOM 2loop)}$,

- Using different RI/SMOM schemes (using various spinor projections) to check the systematic errors
- Four quark operator for B_K

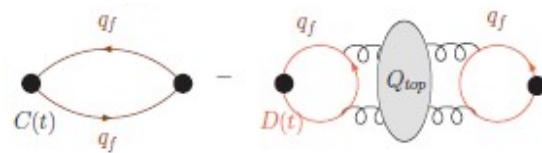
Z(BK) systematic errors



$$Z_{B_K}^{\text{NDR}}(\mu = 2 \text{ GeV}, a^{-1} = 2.31 \text{ GeV}) = 0.964(25)[2.6\%]$$

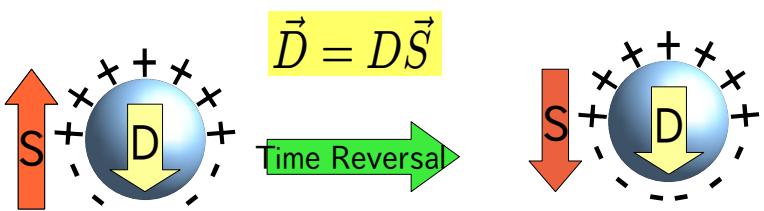
$$Z_{B_K}^{\text{NDR}}(\mu = 2 \text{ GeV}, a^{-1} = 1.73 \text{ GeV}) = 0.936(30)$$

Tackling disconnected quark loop



- Brute force calculation
- Smearing for Hadron wave func etc.
- Low eigen-mode averaging
- Flavor singlet meson η' ($U(1)_A$ problem)

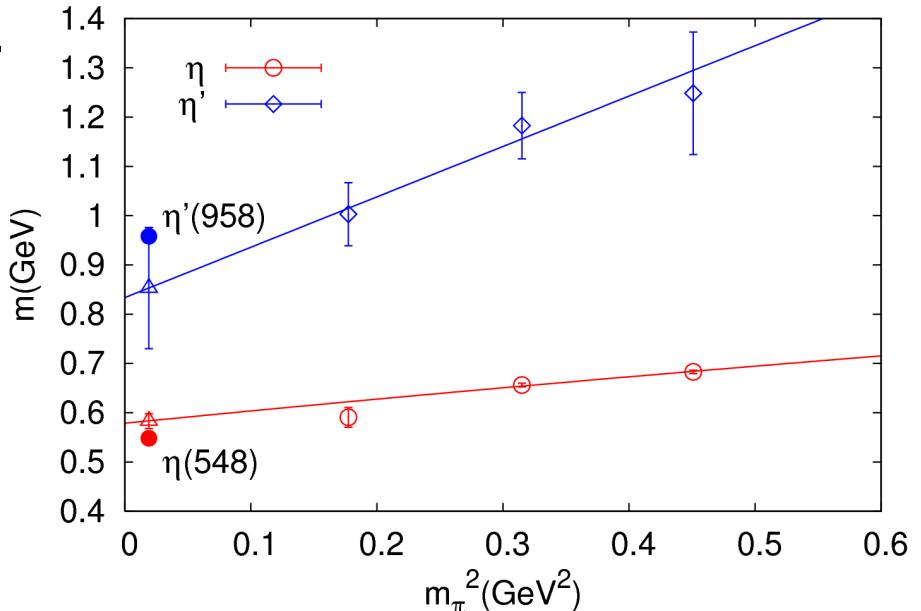
Electric Dipole Moment (EDM) of Proton/Neutron (Strong CP problem)



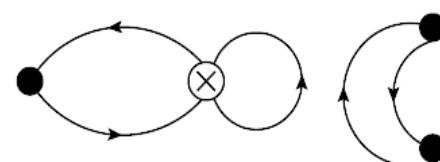
$$D_n = \lim_{q^2 \rightarrow 0} \frac{e}{2m_N} F_3(q^2)$$

- vacuum angle θ , is implemented on lattice with analytical continuation:

$$\theta \rightarrow -i\theta$$



- ~15 % stat. error on m_π^2 arXiv:1002.2999
- $N_f=2$ [K. Hashimoto] & $N_f=2+1$ [Q. Liu]
- Challenging yet important calculations such as $\Delta I=1/2$ $K \rightarrow \pi\pi$, ε'/ε



, or $(g-2)_\mu$ light-by-light, Strange quark contents in Nucleon (Dark matter detection)

Summary

- Lattice QCD is becoming a practical tool for non-perturbative calculation from first principles in particle physics.
(bridge between experiment and theory)
- DWF, preserves chiral symmetry, is optimal for (Weak) Matrix elements (\rightarrow R. Van de Water's talk), which are necessary ingredients for precise checks of the Standard Model of particle physics and beyond.
- Calculations using DWF $N_f=2+1$ are being carried out thanks to many developments in theory, hardware, and algorithms.
- New hardware QCDCQ (BG/Q)
- Sample of Lattice activities:
 - A new chiral quark formalism [M. Creutz, T. Misumi]
 - Hadron spectrum and quark masses from QCD+QED simulation.
 - New renormalization schemes RI/SMOM
 - Weak Matrix Elements B_K , ϵ'/ϵ , B & D Physics
 - disconnected diagrams, η' , Proton/Neutron EDM, strangeness in Nucl ..

Appendix

Dynamical QCD simulation

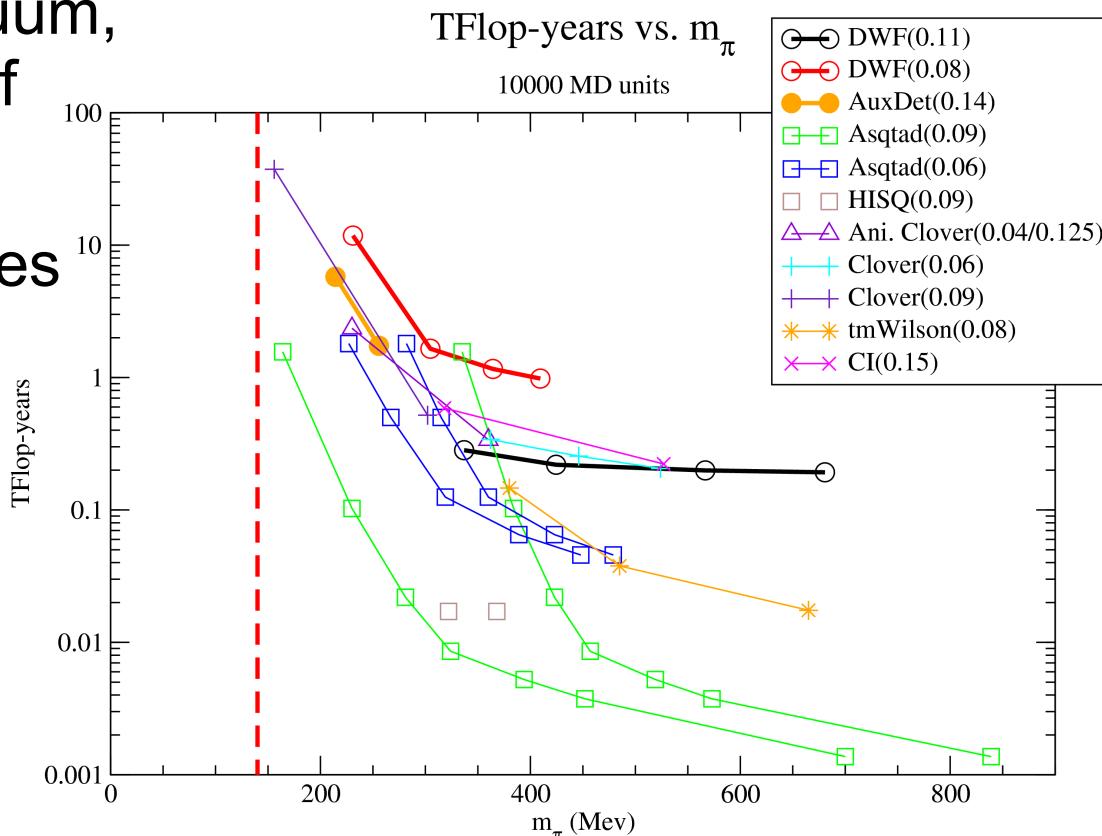
- 1. Accumulate samples of vacuum, typically $O(100)$ - $O(1,000)$ files of gauge configuration
- 2. Measure physical observables on the vacuum samples
- Algorithmic developments

- Rational Polynomial HMC for **odd number of flavors**
- multi-”time” step integrator **separates UV and IR modes**

$$\delta\tau_{\text{gluon}} \ll \delta\tau_{\text{quark,UV}} \ll \delta\tau_{\text{quark,IR}}$$

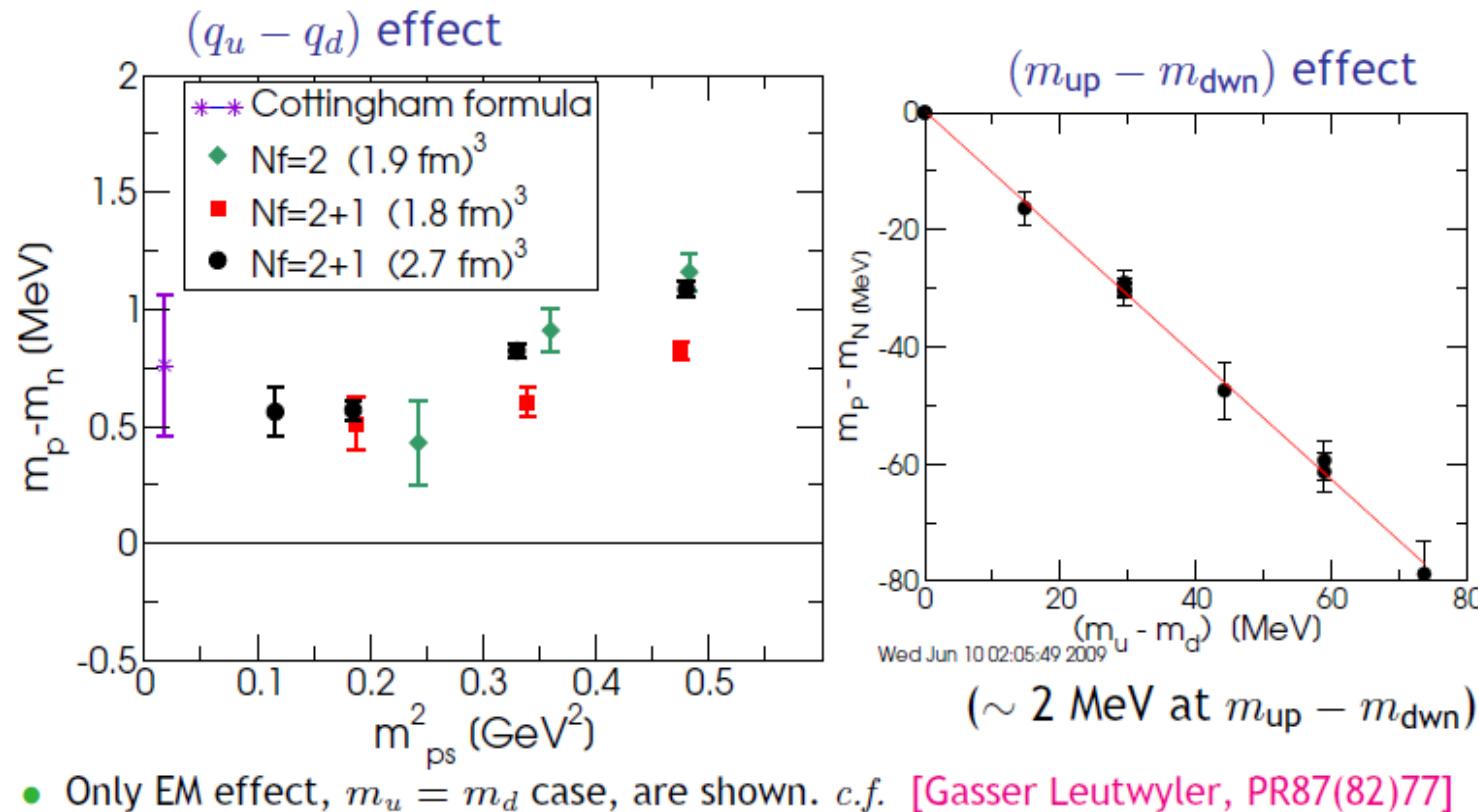
- **Preconditions** by heavy quarks/domain decomposition for Dirac determinants

$$\det(D + m) = \det(D + \textcolor{red}{m}') \times \det(D + m)(D + \textcolor{red}{m}')^{-1}$$



- Hardware developments

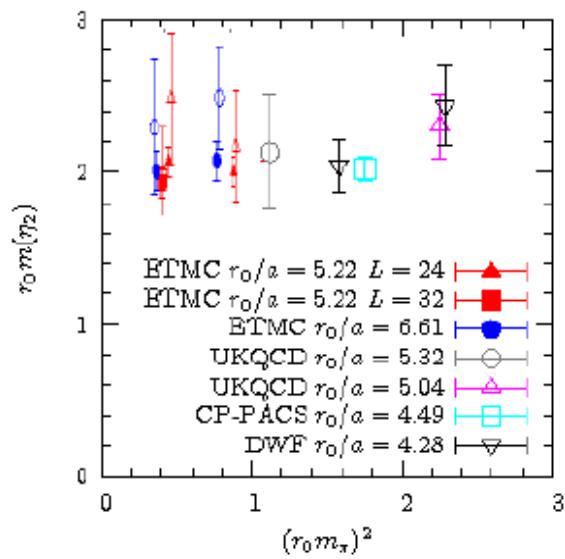
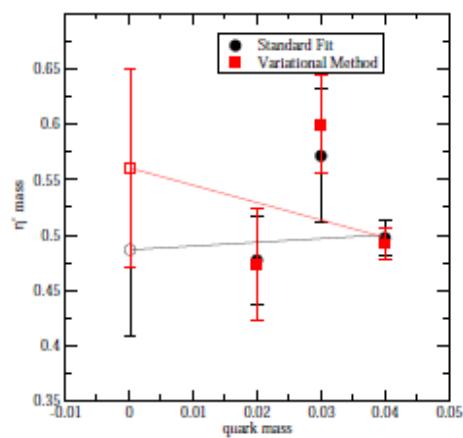
Proton/Neutron splitting



$$M_N - M_p|_{\text{EM}} = -0.76(30) \text{ MeV}$$

$$M_N - M_p|_{\text{quark mass}} = 2.05(30) \text{ MeV}$$

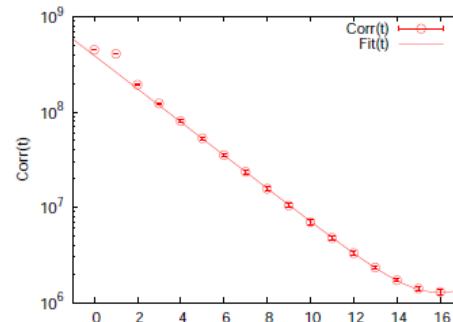
Eta' results for Nf=2 & 2+1



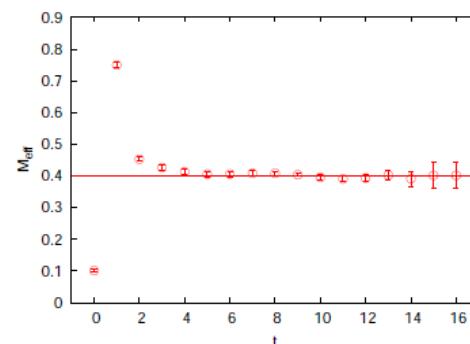
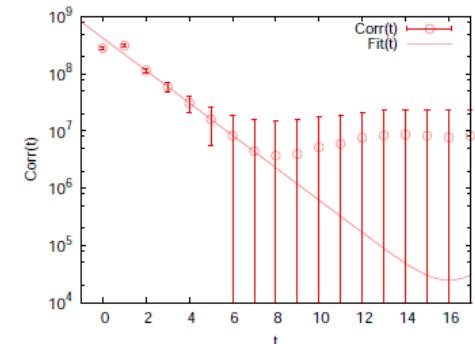
[Nf=2 K. Hashimoto]

$m_{\eta'}$	$m_{\eta'}^{\text{phys}}$ [MeV]	$m_{\eta'} r_0$	Fit and chiral extrapolation
0.480(78)	738(121)	2.05(33)	(Standard) AWTI
0.487(78)	748(120)	2.08(33)	(Standard) linear
0.532(82)	819(127)	2.28(35)	(Variational) AWTI
0.560(89)	862(130)	2.40(36)	(Variational) linear

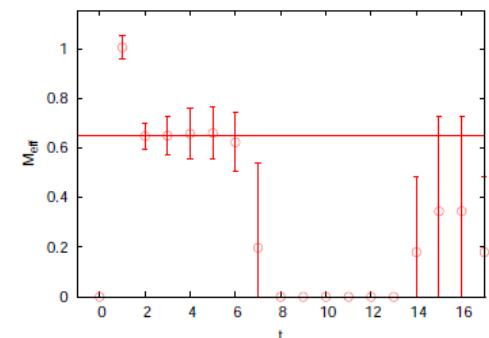
$$m_\eta = 0.401(11) = 694(19) \text{ MeV}$$



$$m_{\eta'} = 0.653(82) = 1.13(14) \text{ GeV}$$



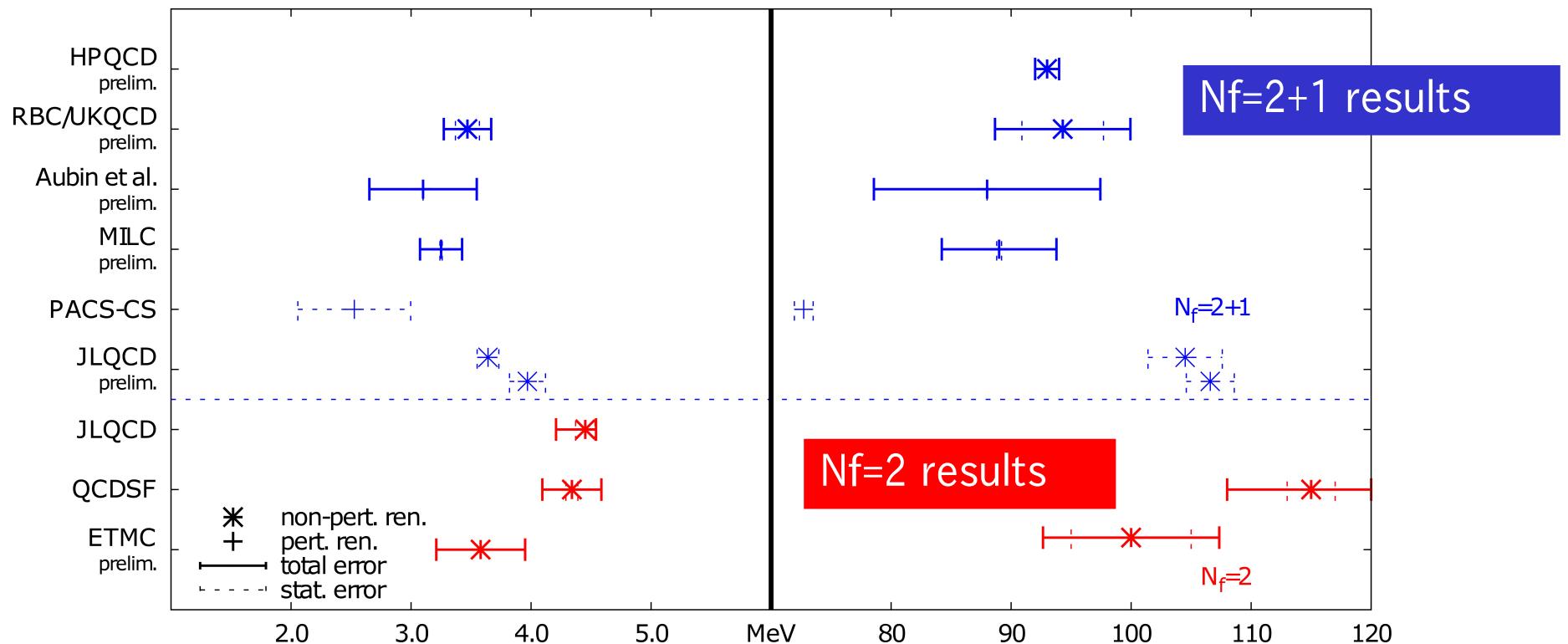
[Nf=2+1 Q. Liu Lattice2009]



Status of Light quark masses

(w/o QED calculation)

QED effects are removed using Dashen's theorem



$$\bar{m}(\overline{\text{MS}}, 2\text{GeV}) = (m_u + m_d)/2$$

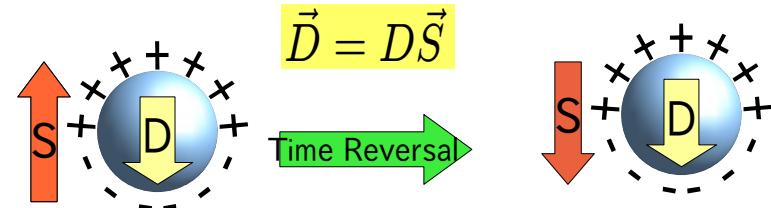
$$m_s(\overline{\text{MS}}, 2\text{GeV})$$

[E. Scholtz Lattice09]

Proton/Neutron EDM on Lattice

Permanent Electric Dipole Moment (**EDM**) is a signature of **CP** (or Time reversal) symmetry **violation**.

A source of **CP** violation :



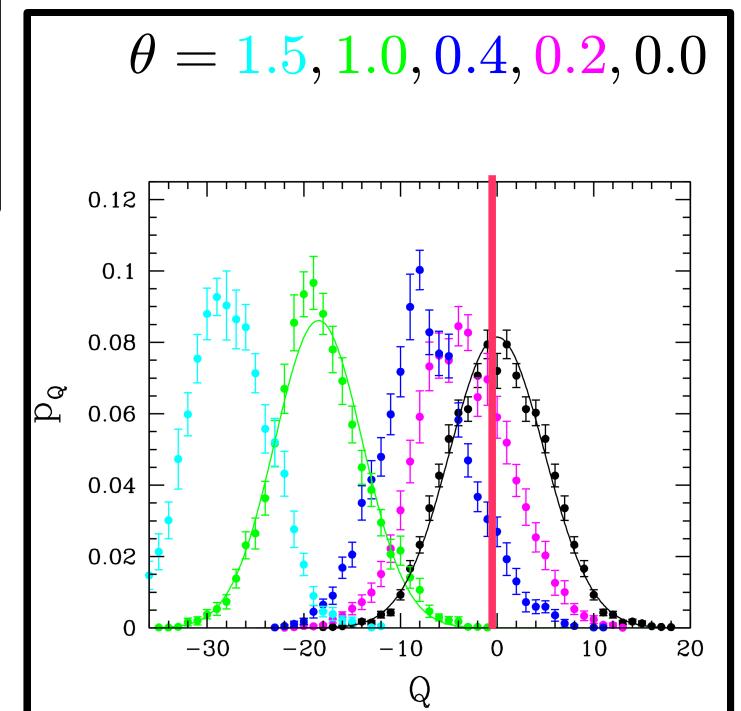
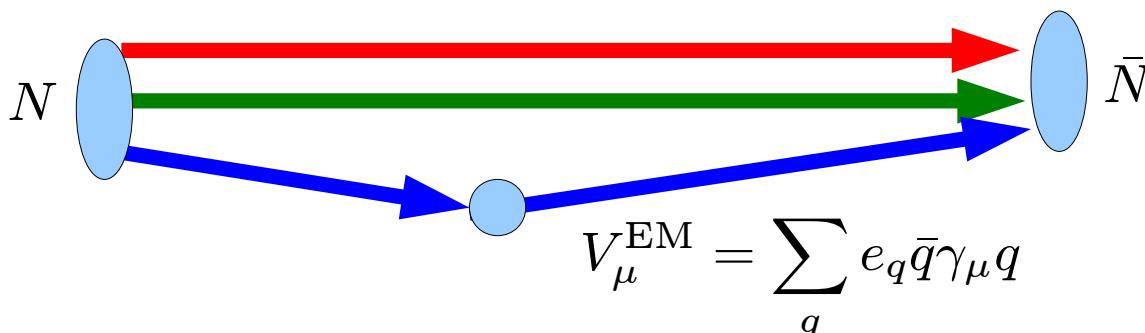
Strong CP: vacuum angle θ , is implemented on lattice with analytically continued to pure imaginary (Monte Carlo simulation)

$$\theta \rightarrow -i\theta$$

EDM is measured through the electric form factor $F_3(q^2)$

$$D_n = \lim_{q^2 \rightarrow 0} \frac{e}{2m_N} F_3(q^2)$$

$$\begin{aligned} \left\langle N_s(\mathbf{p}') | V_\mu^{EM}(\mathbf{q}) | \bar{N}_s(\mathbf{p}) \right\rangle_\theta &= F_1(q^2) \gamma_\mu + F_2(q^2) \frac{q_\nu \sigma_{\mu\nu}}{2m_N} \\ &+ i\theta F_3(q^2) \frac{q_\nu \sigma_{\mu\nu} \gamma_5}{2m_N} + \dots, \quad q = p' - p \end{aligned}$$



Results of F_3

valence theta = sea theta = 0.2 (left) and 0.4 (right)

Dipole ansatz

$$F_3^\theta(q^2) = \frac{F_3^\theta(0)}{(1 + q^2/M^2)^2}$$

DWF simulation is planned for remove systematic errors (valence theta)

